The Consummate Engineer

Semiconductor Fundamentals (Part 1) Resistivity and Doping

Embedded systems—or even modern electronics in general—couldn't exist without semiconductor technology. In this new article series, George delves into the fundamentals of semiconductors. In Part 1, he examines the math, chemistry and materials science that are fundamental to semiconductors, with a look at the basic structures that make them work.

COLUMNS

By
George Novacek

Without semiconductors, there would be no electronics as we know them today. With that in mind, I want to cover some basic concepts in semiconductors, starting with resistivity and doping. But first I want to take a few steps back into the history of semiconductors and talk about their early days. A great many scientists participated in the development of semiconductors. Thomas Johann Seebeck was the first to describe semiconductor behavior as early as 1841. And the lineup seems endless, including Michael Faraday, Alexandre Becquerel, Walter H. Schottky, William Shockley, Herbert Mataré and many others.

To compare different materials and their electrical properties, a material-specific resistance called "resistivity" has been introduced. It is designated by the symbol ρ (Greek letter Rho), expressed in Ohm-meters (Ω-m) and specified at 20°C (68°F) unless otherwise noted. All materials can be characterized by their electrical resistivity, among other properties. Resistivity, however, depends not only on the material being measured but also on its temperature and other factors.

Conductivity is sometimes used instead of resistivity. It is the inverse value of resistivity, that is 1/ρ. Materials can be divided into three major categories: conductors, semiconductors and insulators. **Figure 1** depicts resistivity ranges of the three groups.

CURRENT FLOW

What makes electrical current flow in a material? The two fundamental mechanisms are the movement of ionized atoms and the movement of electrons in the material. The former can be seen in electrolytes, whereas the latter is what is happening in conductors and semiconductors.

Electrons are fundamental building blocks of atoms, with their mass of 9.1×10^{-28} g. They carry negative charge q of 1.602×10^{-19} C (Coulombs). All conductors contain a quantity of free electrons. Due to thermal oscillations, the electrons move around in a chaotic way. Their collisions with atoms alter their trajectories and speed, but when there is no electric or magnetic field present, they travel in straight lines at constant speed.

The time between two collisions τ and the speed at which the electron travels v determine the distance L the electron has traveled:

$$L = v \times \tau$$

The overall motion of the electrons causes

no electrical current to flow, because the sum of all the electron motions in many directions add up to zero. However, in the presence of an external power field, such as an electric field, electrons are accelerated in the direction of the field. The increase in their speed v_d is quite small, corresponding to a fraction of a percent of the original speed v. If the concentration of free electrons per cubic centimeter (cm^3 = 0.061 cubic inches) is n, then $n \times v_d$ electrons move through a conductor with 1 cm^2 (0.15 in^2) cross section exposed to a constant power field every second. With v_a being the average electron velocity increase, there will flow electric current of density J:

$$J = q \times n \times v_a$$

Conductors have very low resistivity—less than about $5x10^{-3}$ Ω-m. They contain an abundance of free electrons between their atoms. If there is a potential difference—that is, a voltage across the conductor—the free electrons travel through the material from the negative to the positive terminal. In other words, they cause an electric current to flow. The amount of electrons capable of flowing through the conductor depends on the conductor's resistivity, which is, to some degree, affected by temperature.

Insulators generally are made of non-metallic materials with very few free electrons in their atomic structure. Therefore, they have high resistivity—typically one million Ω-m and higher. Insulators' resistivity is mostly independent of temperature, although some materials, such as plastics, may disintegrate and lose their isolating characteristics when exposed to a high temperature.

"DOPING" SEMICONDUCTORS

Early semiconductors were made of germanium (Ge) but the most commonly used materials nowadays are silicon (Si) and gallium arsenide (GaAs). In terms of their resistivity, semiconductors are generally poor conductors as well as poor isolators, located between the two as shown in Figure 1.

Pure semiconductor materials, such as silicon, suffer from shortages of free electrons, because their atoms, arranged in a "crystal lattice," have their valence electrons (those in the outermost orbit) mutually interlocked. Consequently, not many free electrons are available to conduct current, and the resistivity values are quite high. A crystal of pure silica, which is a silicon dioxide we know as glass, for example, is a good isolator (**Figure 1**).

By adding or replacing certain donor or acceptor atoms into the lattice—that is, by

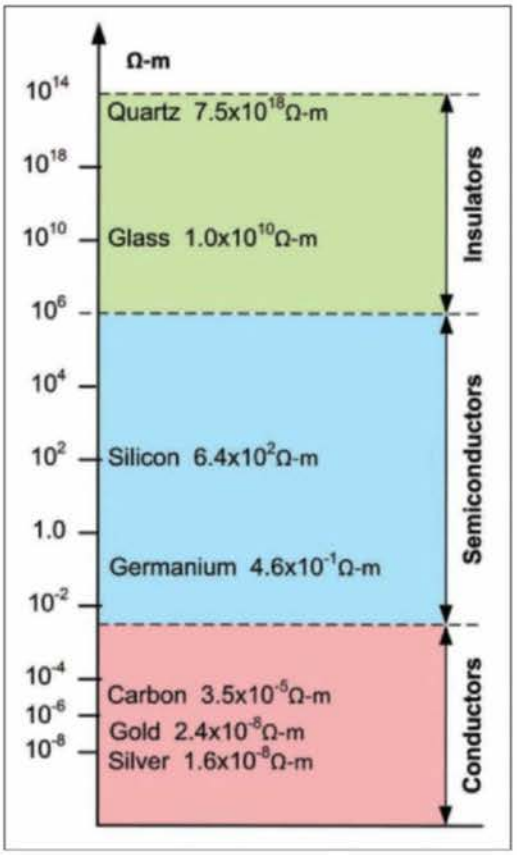


FIGURE 1
Resistivity of some materials

adding a tiny amount of another element into the base of chemically pure germanium or silicon—more free electrons or holes are generated. This, in turn, can enhance the semiconductor's conductivity. Addition of impurities on the order of approximately one atom per ten million of Si or Ge atoms is called "doping," and the doped element becomes a semiconductor. It should be noted that semiconductor characteristics, namely their resistivity, are affected by temperature, humidity, electric and magnetic fields, light, radioactivity, pressure and other factors.

As previously mentioned, the most prevalent base material used today is

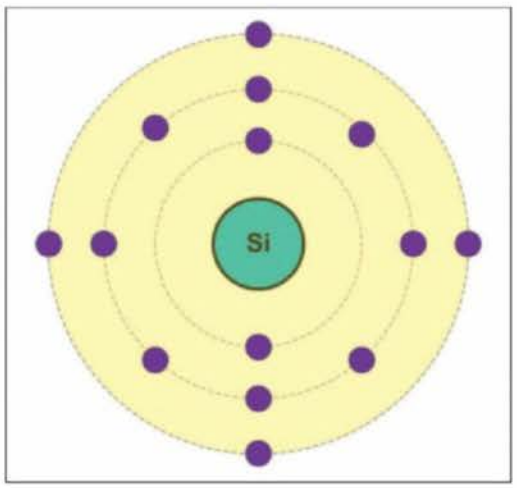


FIGURE 2
Structure of a silicon atom with four electrons in its outer valence orbit

FIGURE 3
Silicon crystal lattice

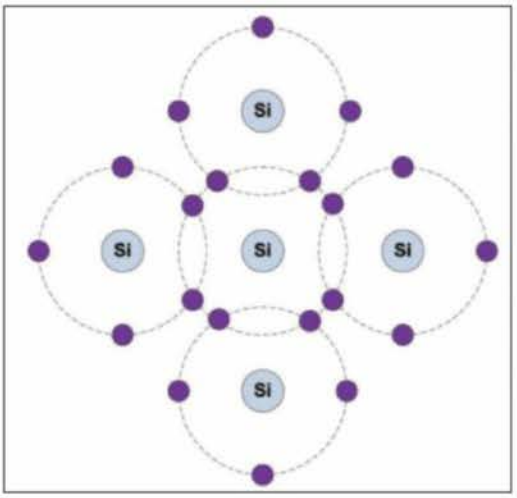
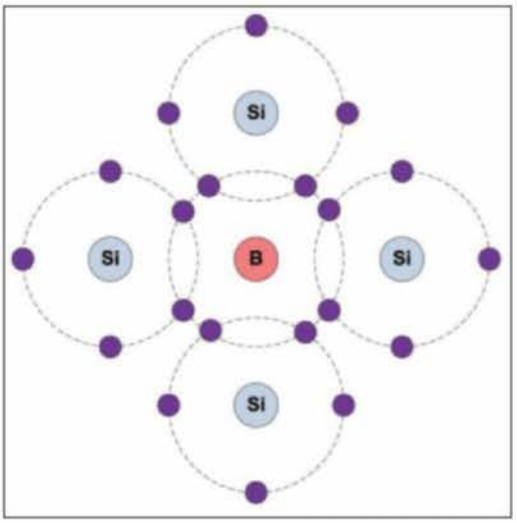


FIGURE 4
Silicon lattice doped with boron



ABOUT THE AUTHOR

George Novacek was a retired president of an aerospace company. He was a professional engineer with degrees in Automation and Cybernetics. George's dissertation project was a design of a portable ECG (electrocardiograph) with wireless interface. George has contributed articles to *Circuit Cellar* since 1999, penning more than 120 articles over the years.

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As previously mentioned, the most prevalent base material used today is silicon. The silicon atom has 14 electrons orbiting its nucleus, four of which—the valence electrons—are in its outermost orbit, as shown schematically in **Figure 2**. Each atom shares those valence electrons with neighboring atoms, thus bonding to form a very stable crystalline structure, also known as a crystal lattice (**Figure 3**).

By doping the silicon base with certain impurities, we create positive and negative poles, allowing an electric current to flow. Arsenic (As), antimony (Sb) or phosphorus (P) are typical impurities introduced to the crystalline structure and sharing their outer electrons with the adjoining atoms. They have five valence electrons in their outer orbits and are, therefore, referred to as "pentavalent impurities." Because only four of the silicon orbital electrons bond, one electron becomes free and will be able to carry current when a voltage is applied.

Because the arsenic, antimony or phosphorus elements donate free electrons, they are referred to as "donors." Antimony and phosphorus are the most frequently used donors. The excess free electrons carry negative charges, and therefore, a doped semiconductor is called "N-type." The electrons are majority carriers and the resulting holes are minority carriers. As a stimulus—a voltage, for example—frees the electrons from the silicon atoms, they are quickly replaced by the free electrons obtainable from the donors. Nevertheless, it still leaves more negatively charged electrons. For that reason, the N-type semiconductor contains more electrons than holes.

In contrast, a trivalent impurity used for doping has only three valence electrons in the outer orbit. Such impurities would be aluminum (Al), boron (B) or indium (In). Doping with these creates a shortage of electrons, and this provides the semiconductor with a lot of positively charged carriers known as holes. While electrons from the adjacent atoms try to fill the holes, they leave other holes behind. The result is that, we might say, the holes move a positive charge through the crystalline structure.

And because of the resultant shortage of electrons, the doped crystal structure becomes a positive pole. The trivalent impurities are also called acceptors, since they accept free electrons in the semiconductor crystal. Boron is frequently used to create this "P-type" semiconductor (**Figure 4**). Here the positive holes are the majority carriers and the free electrons are minority carriers. In contrast to the N-type semiconductor, the acceptor density is greater than its donor

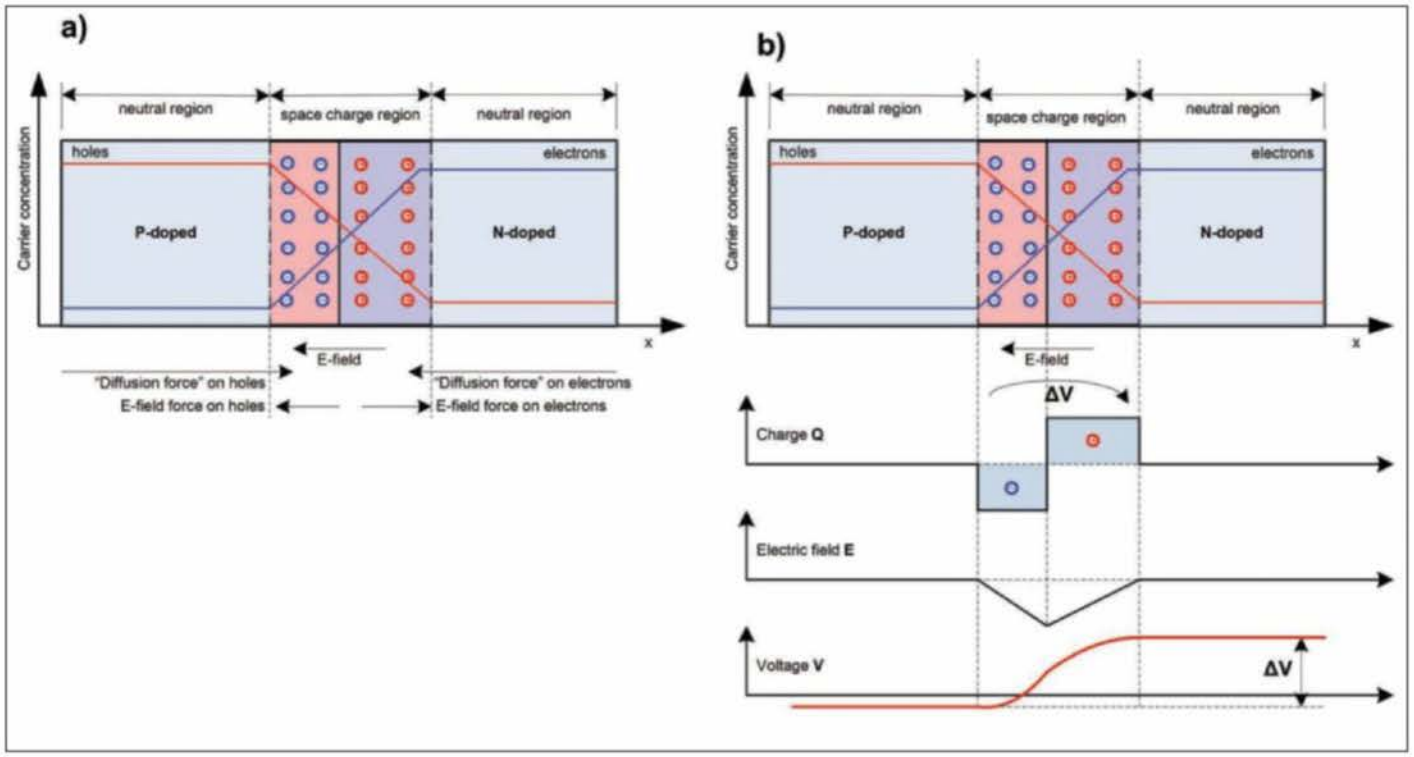


FIGURE 5
Behavior of P-N Junction when (a) the junction is in equilibrium condition, and (b) when a forward voltage is applied.

density, and there are more holes than electrons in the P-type semiconductor.

P-N JUNCTION

Now, let us consider what happens when a P and an N semiconductor are joined together to form a P-N junction. Immediately, some free electrons from the N-atoms begin to migrate across the junction and combine with the holes in the P-atoms, producing negative ions. This leaves positive donor ions in the N-material, to which holes from the P-material tend to migrate (**Figure 5**). Consequently, a thin layer of the P-type material along the junction contains negatively charged acceptor ions, while a thin layer of the N-type material on the opposite side of the junction becomes positive.

This movement of electrons and holes across the junction is called "diffusion." The process continues until equilibrium is reached. A potential barrier around the junction is created and the regions on either side of the junction are depleted of any free carriers. This area around the P-N Junction is referred to as the "depletion layer." The potential barrier depends on the materials used and on temperature, and is about 0.35 V for germanium and 0.7 V for silicon junctions. We perceive it as the forward voltage drop in specifications.

If we apply a positive voltage to the P-side of the junction and negative voltage to the N-side of the junction—that is, we apply a forward voltage—extra energy will be provided for the free electrons and holes to overcome the potential barrier, and electric current will flow.

When we connect the junction in a reverse polarity—that is, a positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material—two things happen. The positive voltage attracts electrons toward the positive electrode and away from the junction, while the holes in the P-type material are also attracted away from the junction and toward the negative electrode. As a result, the depletion layer increases in width due to the lack of electrons and holes. Its impedance increases, almost becoming an insulator. The high potential barrier is thus created, preventing current from flowing through the junction.

I think that's enough about electrons and doping for now. Next month we'll continue this series, first taking a closer look at diodes, then at other devices comprising more than two P-N junctions.

The Consummate Engineer

Semiconductor Fundamentals (Part 2) Diodes in Detail

In Part 1, George examined the basic structures that make semiconductors work. But a lot more needs to be said about diodes, which are a key element of semiconductors. In Part 2, George dives deeper, this time looking at the current flow, depletion layer and electron physics that are involved in diode operations. He covers various types of diodes and the details of their operations.

COLUMNS

By
George Novacek

Last month we looked at what happens when we join P and N materials, creating a P-N junction. To refresh your memory, free electrons from the N-atoms migrate across the junction and combine with the holes in the P-atoms, producing negative ions. This leaves positive donor ions in the N-material to which holes from the P-material tend to migrate. (See **Figure 1**, which was also shown in Part 1.) The result is that the thin layer of the P-material adjacent to the junction contains negatively charged acceptor ions, while the layer of the N material on the opposite side of the junction contains positive ones. This diffusion of electrons and holes continues until equilibrium is reached. A potential barrier around the junction is created, and the regions on either side of the junction, called the "depletion layer," contain no free carriers.

If we apply a positive voltage to the P-side of the junction and negative voltage to the N-side, free electrons and holes will be given extra energy to overcome the potential barrier, and electric current will flow. When the polarity is reversed, the depletion layer increases in width, due to the lack of electrons and holes. Its impedance increases too, almost becoming an insulator, preventing current from flowing through the junction. A P-N junction, therefore, conducts electrical current in one polarity and blocks it in the opposite polarity. This the basis of a solid-state diode operation.

DIODE BASICS

Diodes contain only one P-N junction. Nowadays, silicon is the most common material. Germanium and selenium were used in the past. You can also find diodes made of gallium arsenide. **Figure 2** is the I-V (current vs. voltage) diagram illustrating the principle of a diode operation. This characteristic is described mathematically by the Shockley diode equation:

$$I = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$$

where I is the diode current, V_D is the voltage across the diode, V_T is the thermal voltage and n is the ideality—also known as quality factor or emission coefficient. The n factor is usually between 1 and 2, based on the type of the diode and its manufacturing process. The thermal voltage V_T is approximately 25.85 mV

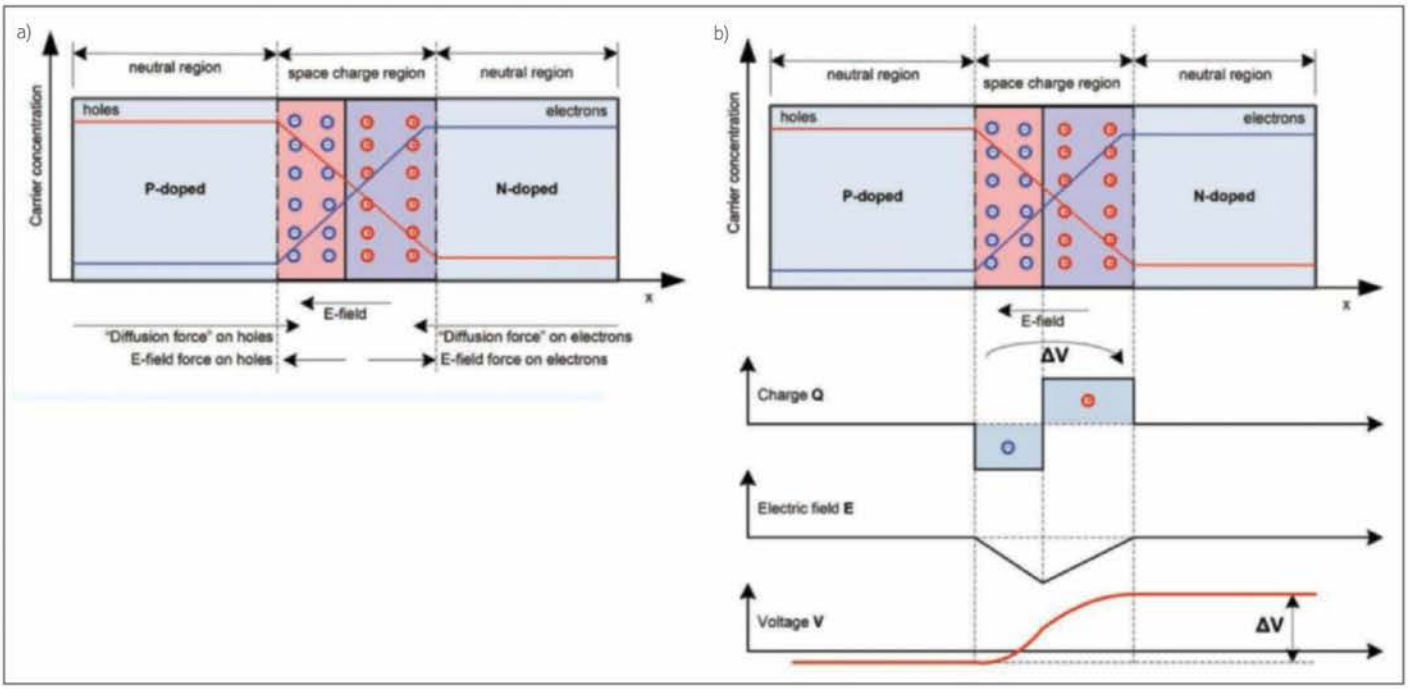


FIGURE 1
Behavior of P-N Junction. (a) in equilibrium condition; (b) when a forward voltage is applied

at 300°K (26.85°C = 80.334° F). It is defined as:

$$V_T = \frac{kT}{q}$$

where k is the Boltzmann constant (1.380649 × 10^{-23} J/K (joules per Kelvin)), T is the absolute temperature and q is the magnitude of an electron charge (1.602176634 × 10^{-19} coulomb) [1].

Referring again to Figure 2, a small forward voltage results in a small forward current, until a knee voltage is reached—typically 0.7 V for silicon diodes. After that, the current will grow quickly, depending on the diode's internal resistance which, in most cases, is very small. When reverse voltage is applied, a reverse current (leakage)—which depends on the device and varies with temperature—will flow. The leakage, when compared to the forward current, should be negligible. At some level, the reverse voltage will cause a breakdown. Exceeding the reverse breakdown voltage can damage many devices, while some, such as Zener diodes, take advantage of it. Zener diodes use this effect for voltage limiting or stabilization. Ideally, the internal resistance of a Zener diode in its avalanche region should be zero. But, because it's not, the stabilized voltage will change slightly with the current.

There are many types of diodes tailored for a specific function. The most prevalent are ordinary signal and rectifier diodes used to conduct current in one direction only. The drawback of silicon diodes is their forward voltage of about 0.7 V—depending on the device and the current. It affects circuits for low-level signals and power rectifiers, where it causes increased heat dissipation.

This problem is reduced by Schottky diodes with the forward voltage drop of about 0.15 V to 0.45 V. Schottky diodes are constructed from a metal-to-semiconductor contact, exhibiting faster reverse current recovery. Their capacitance is smaller than their P-N counterparts. For that reason, they can be found in switching power supplies and both

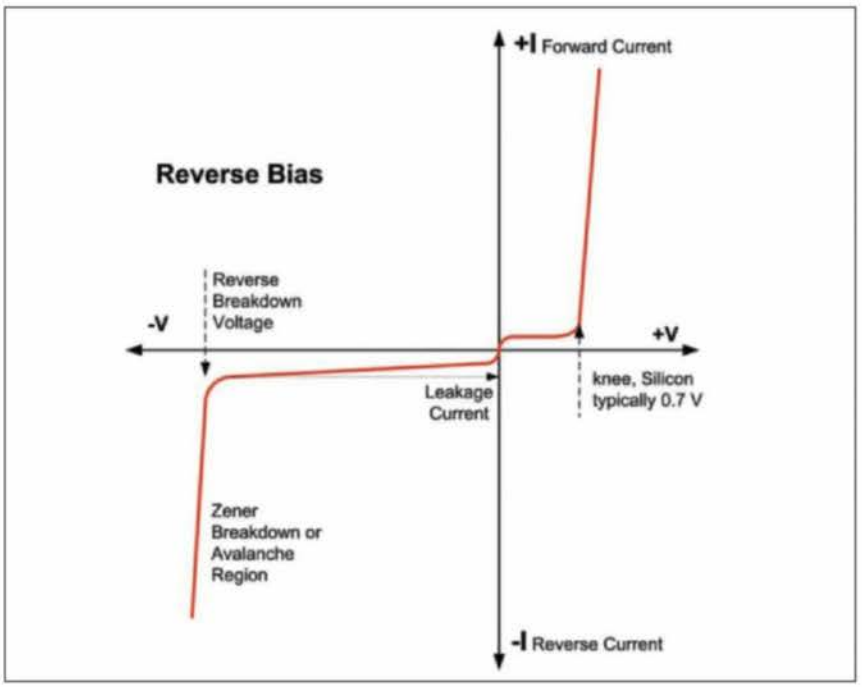
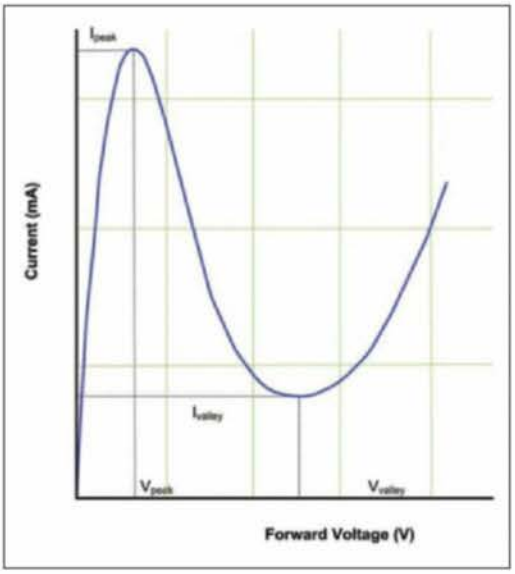


FIGURE 2
I-V Characteristic of a diode (not to scale)

COLUMNS

FIGURE 3
Typical tunnel diode I-V graph



high-speed and radio frequency (RF) circuits. On the negative side, their reverse voltage is limited to about 50 V, and the leakage is higher than that of silicon diodes.

MORE TYPES OF DIODES

Let's look at other diode types. I already mentioned Zener diodes. Avalanche diodes are similar—often mistakenly considered Zener diodes—but their reverse voltage breakdown mechanism is a bit different. However, their temperature coefficient is of opposite polarity to Zener diodes, so that they can be successfully used in combination with Zeners for temperature compensation of voltage stabilizers.

Similar in their principle are TransZorbs made by Vishay Semiconductor—also called TVS (Transient Voltage Suppressor) diodes. They are used for overvoltage circuit protection. TVS diodes come as unipolar—analogous to a single Zener—and bipolar, which could be modeled by two series-opposite Zeners. They are significantly faster than Zeners, and can absorb a lot of pulse energy (see my article "Overstress Protection" in *Circuit Cellar* 330, January, 2018.) Diacs—commonly used for voltage triggering—and their much faster cousins, Perun diodes, come under the same category and can be modeled by two series-opposite Zener diodes.

The "constant-current" diode is a misnomer. It is not a diode at all, but rather a JFET (junction field effect transistor), with its gate and source electrodes shorted. In conjunction with a Zener diode, it provides a very stable voltage source. Tunnel diodes, also called Esaki diodes, exhibit a negative resistance region in their I-V characteristic, which is due to quantum tunneling. These diodes are very fast and work as oscillators, small signal amplifiers or simple bi-stable circuits at high frequencies. Gunn diodes are similar and have similar applications, but are faster, allowing construction of microwave oscillators. **Figure 3** depicts the typical tunnel diode I-V characteristic.

Light-emitting diodes (LEDs) comprise a direct band-gap semiconductor, typically gallium arsenide (GaAs). Charge carriers, while crossing the junction where they recombine with the majority carriers on the other side of the junction, emit photons. Depending on the material used, different colors of light can be generated, from infrared to the near ultraviolet. Various colors, including white, can be obtained by mixing several base colors and by scintillator coating.

LEDs are sensitive to light and can be used as cheap photo detectors. Coupled with photo detectors—for example, photo diodes, photo transistors, photo SCRs and so on—they form the basis for opto-isolators. Today, efficient, powerful LEDs are replacing traditional incandescent lights. By placing a specially formulated LED in a resonant cavity, we obtain a laser. Lasers are used in high-speed communications via fiber optics, and for optical storage devices such as CDs, DVDs and Blue-rays.

All P-N diodes have their forward voltage linearly dependent on the temperature:

$$T_J = (m \times V_F) + T_0$$

where T_J is the junction temperature in °C, m is a device-specific slope in °C/V, V_F is the forward voltage drop and T_0 is a device-specific intercept temperature in °C. As is apparent from the equation, the temperature dependence is device-specific, but it is typically -2.3 mV/°C. Many

ABOUT THE AUTHOR

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Reference [1] as marked in the article can be found there.

RESOURCES

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ICs contain an integral thermal diode for monitoring their internal temperature or for external temperature measurement. Thermal diodes are also the building block of Peltier thermoelectric modules (see my two-part article "Thermoelectric Cooling" in *Circuit Cellar* 336 and 337, July and August 2018.)

Semiconductors are also sensitive to light, which is not always a desired characteristic. That's why semiconductors are packaged in light-blocking materials, unless they are photodiodes used for the detection of light. There are many uses for photo-sensitive semiconductors, from the aforementioned opto-isolators and fiber-optic communications to light sensors, solar cells and others.

PIN diodes use a so-called "high level injection," forming an intrinsic I region between the P and N materials that is saturated with charge carriers. The intrinsic layer is an undoped semiconductor. PIN diodes find their use in RF circuits, as ionizing radiation detectors and photo detectors. Because the central I layer can withstand high voltages, the PIN structure is used in IGBTs, power MOSFETs and thyristors.

Super barrier diodes are rectifiers based on the Schottky diode structure. Compared with the regular P- N rectifiers, they feature lower forward voltage drop, high surge-handling capability and low reverse leakage current. Diodes doped with gold (Au) or platinum (Pt) boast improved speed of recombination of minority carriers. They can operate at RF frequencies and are faster than regular P-N diodes (though not as fast as Schottky), but their forward voltage drop is higher than regular P-N diodes. Their reverse voltage leakage is lower than that of Schottky diodes. Their typical representative is the ubiquitous 1N914.

A step recovery diode (SRD) can generate very short pulses, and finds its use in microwave electronics. In the same category, we find varistors—also called varicaps or varactors—which take advantage of their voltage-dependent capacitance between the P and N electrodes. These are used as voltage-controlled capacitors in all kinds of RF circuits. In fact, the classic tuning capacitor is almost impossible to find any more. Finally, we should mention stabistors, which are silicon diodes with a very stable forward voltage drop. These are used as low-voltage reference sources with extremely low dependency on the operating current and temperature.

In this article, we've covered all-things-diode in a nutshell. Next month, in Part 3 of this article series, we'll take a closer look at devices with more than two P-N junctions.

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The Consummate Engineer

Semiconductor Fundamentals (Part 3) Transistor Topologies

In Part 2, George discussed devices built with one P-N junction, appropriately named diodes. In this article, he considers devices with more junctions. He starts with two and looks at the ubiquitous, three-terminal bipolar junction transistor (BJT). George looks at the math, science and circuitry of these devices.

COLUMNS

By
George Novacek

Last month we dived deeper into diodes. Now it's time to consider devices with more junctions. Let's start with the three-terminal bipolar junction transistor (BJT). Its terminals are called collector (C), emitter (E) and base (B). **Figure 1** explains its construction, which is essentially a combination of two junction diodes. Based on their connections, we have two basic structures: PNP (Figure 1a) and NPN (Figure 1b), with the transistors designated accordingly. PNP and NPN devices with similar characteristics are called complementary pairs. In the early days, germanium (Ge) was used as the base semiconductor material and although germanium NPN transistors existed, the PNP variety ruled. The first NPN transistor I got to use was the silicon (Si) type.

The first point-contact transistor was the result of the work of American physicists John Bardeen, Walter Brattain and William Shockley in 1947—an achievement for which they received the Nobel Prize in Physics. As it usually happens with many inventions, the transistor was developed independently in Europe in 1948 by Germans Herbert Mataré and Heinrich Welker. The bipolar junction transistor was then developed and patented by William Shockley in 1950 at Bell Labs.

Germanium transistors manufactured in the '50s by the diffusion method had many growing pains. One was a poor frequency response due to large capacitance of the diffused electrodes. But the manufacturing technology improved and by the '60s we had ultra-high frequency (UHF) devices, for example the amazing (for their time) AF139 and AF239 PNP transistors. Germanium devices suffered from high leakage, relatively low operating voltage and, above all, significant temperature dependency. But all that changed with the arrival of the silicon planar NPN transistor.

One issue you have to keep in mind is that transistors are current amplifiers. They're not voltage amplifiers like vacuum tubes before them and field effect transistors (FET) today. BJTs operate in distinct modes. The first is linear, where the collector current $I_C = \beta \times I_B$. β stands for the transistor's current gain—generally greater than 100 in modern devices.

The second mode of operation is saturation, which is used in digital circuitry. The transistor becomes a switch. It is fully turned on with the saturated collector current determined by its type and collector-emitter voltage V_{CE} close to zero. Or it is turned off (cut off) with $I_B = 0$. The collector current I_C would ideally be zero too, but there is always some leakage.

THREE AMPLIFIER CONFIGURATIONS

Let's consider the three fundamental transistor amplifier circuit configurations as seen in **Figure 2**. Because of the present-day prevalence of NPN transistors, I shall use them in my examples whenever possible. We begin with the common base topology (Figure 2a). The base is grounded and, therefore, common to both the input and output. To amplify an AC signal, you'll need to bias the base to overcome the base-emitter diode's forward voltage—around 0.65 V for silicon transistors—and cause a base current I_B to flow. The current gain of the common base topology is less than 1 because the collector current I_C flows through the emitter as well. The input impedance of the common base topology is very low. The voltage gain, however, is high—provided the load resistance R_L is also high. It is defined by Equation 1:

$$A_V = \frac{V_{out}}{V_{in}} = \frac{I_C \times R_L}{I_E \times R_{IN}} \quad [1]$$

Common base configuration is used primarily in radio frequency (RF) circuits because it minimizes frequency-limiting collector-base capacitance. Common (grounded) emitter configuration is commonly used in amplifiers as well as switching circuits because it has the highest power gain. Similar to common base, the input impedance is somewhat low, but can be increased, at the cost of gain, by a small resistor between the emitter and ground. Here, the emitter current $I_E = I_C + I_B$. The ratio I_C/I_E is called α and is always less than one. The relationship of the transistor currents can be expressed mathematically as:

$$\alpha = \frac{I_C}{I_E} \quad \beta = \frac{I_C}{I_B} \quad \ldots\ldots \quad I_C = \alpha \times I_E = \beta \times I_B \quad [2]$$

$$\alpha = \frac{\beta}{\beta + 1} \quad \beta = \frac{\alpha}{\alpha - 1} \quad \ldots\ldots \quad I_E = I_C + I_B \quad [3]$$

Common collector topology is better known as emitter follower. It is frequently used for transformation of high impedance input signals to low impedance output. The current gain equals approximately β of the

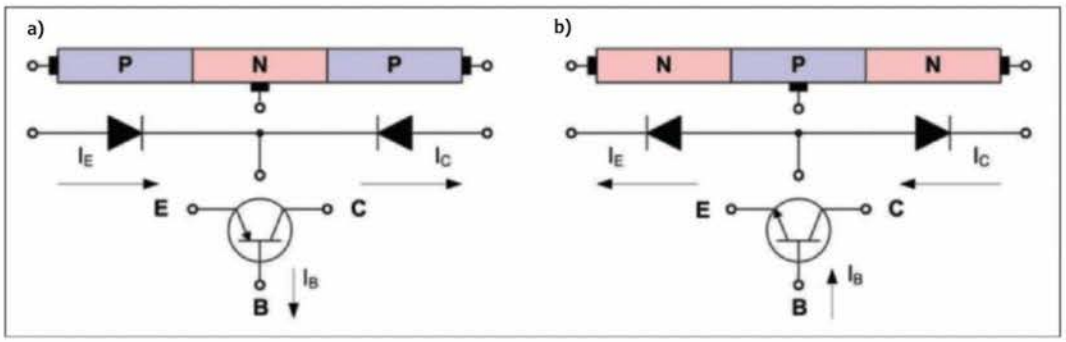

FIGURE 1
Principle of the bipolar junction transistor. PNP (a) and NPN (b)

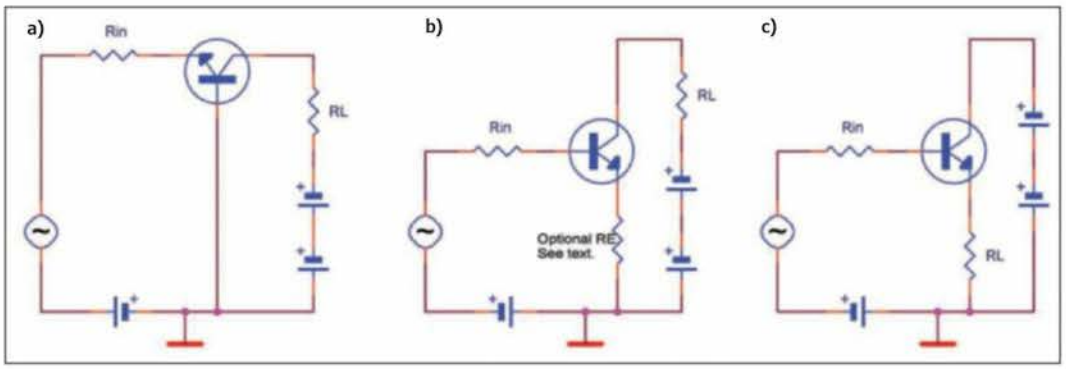

FIGURE 2
Three fundamental configurations of a transistor amplifier: Common base (a), common emitter (b) and common collector (c)

	Common Base	Common Emitter	Common Collector
Input Impedance	Low	Medium	High
Output Impedance	Very High	High	Low
Phase Shift	0 degrees	180 degrees	0 degrees
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

TABLE 1
Summary of characteristics of transistor amplifier topologies

The Consummate Engineer

Semiconductor Fundamentals (Part 4) Amplifiers and FETs

George continues his article series looking at all aspects of the basic structures that make semiconductors work. In Part 4, he shows you some useful discrete transistor circuits and then zeros in on the field effect transistors: Junction FETs and MOSFETs. The discussion includes an examination of some fundamental structures like cascode amplifiers and Darlington transistors.

COLUMNS

By
George Novacek

Last month we exhausted the topic of transistor theory, so now let's look at some useful transistor circuit topology. **Figure 1a** shows you a cascode (not cascade!) amplifier and two versions of Darlington transistor in **Figure 1b** and **Figure 1c**, respectively. The three configurations can be realized with either NPN or PNP or both transistors. The latter would be called a complementary pair.

The cascode amplifier (Figure 1a) can be found in many radio and higher frequency circuits. Compared with the common base amplifier—which is also used as high frequency amplifier—the cascode amplifier features higher input impedance, especially when a small resistor is placed between the Q1 emitter and ground. It also has a higher output impedance—both advantageous for interfacing with tuned circuits. And, last but not least, it has greater bandwidth because the cascode topology eliminates the Miller effect.

The Miller effect causes an increase of the equivalent input capacitance of inverting voltage amplifiers by amplifying the actual capacitance, in our case, between the base and the collector terminals. Predictably, the result is the reduction of the maximum frequency response. The Miller effect, by the way, affects all inverting voltage amplifiers, whether vacuum tube or solid state. It is expressed as:

$$C_M = C \times (1 + A_V) \quad [1]$$

where AV is the voltage gain of the amplifier and C the capacitance between the input and the output—in other words, base to collector in our example.

Because of the cascode amplifier's ability to eliminate the Miller effect, you can often find it as the front end of RF receivers. Transistor Q1 works in common emitter configuration, feeding Q2 working as a common base amplifier. This amplifier can and often is realized with junction (JFET) and metal oxide (MOS) FETs. We'll address that later when we discuss those semiconductors. The drawback of cascode amplifiers is that it's comprised of two transistors with additional parts and usually a higher supply voltage is needed. But then the end result is a top-notch high frequency amplifier. To obtain maximum gain, the load R_L should be as high as possible. In critical applications, a constant current source is used instead of the resistor R_L.

THE DARLINGTON TRANSISTOR

The Darlington transistor (Figure 1b) is named after its inventor Sidney Darlington. It

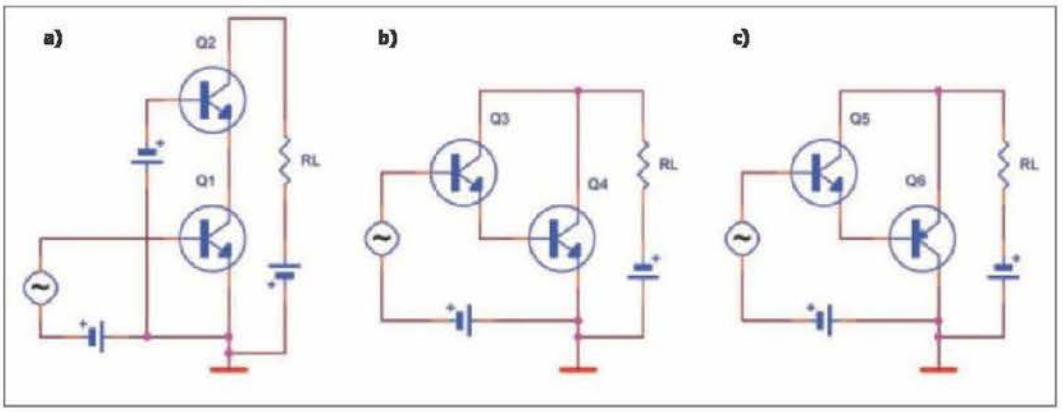

FIGURE 1
Cascode amplifier (a) and Darlington transistor (b, c)

is simply a cascade of two transistors Q3 and Q4, NPN or PNP, in a single package. Its main advantage is a very high current gain, which is approximately the product of the two transistors' gains—this is usually in the thousands. The price you pay for this feature lies in a doubling of the base-to-emitter voltage VBE and increased collector saturation voltage VCEQ4 by VBE, which leads to a higher power dissipation than a single transistor. The Darlington current gain is:

$$h_{FEDarlington} = h_{FEQ3} \times h_{FEQ4} + h_{FEQ3} + h_{FEQ4} \approx h_{FEQ3} \times h_{FEQ4} \quad [2]$$

Unfortunately, the switching speed of the Darlington pair is reduced because Q3 cannot effectively inhibit the base current of Q4. This is to some degree alleviated by the base to emitter resistors integral within the transistor. A complementary pair—one NPN and the other PNP—can be used instead of two transistors of the same type as illustrated by Figure 1c. Either transistor can be NPN or PNP. The Darlington pair's larger phase shift when compared with a single transistor may lead to a system instability.

Another important topology is the balanced, differential, emitter coupled pair—sometimes called a "long tailed pair." It is shown in **Figure 2**. You'll find it in many applications. For example, it is a common input stage of op amps, both discrete and monolithic (ICs). In many discrete component designs, resistors are used in place of the constant current sources. However, for the best performance and especially in the design of IC op amps, constant current sinks and sources are deployed. Besides, in IC manufacturing transistors are easier to implement than resistors. Consequently, to the benefit of monolithic op amps, current sources are almost exclusively used.

Figure 3 shows a couple of discrete circuits that can be useful when an op amp would be an overkill. Figure 3a is a complementary voltage amplifier. With the component values shown it has a gain of 40 dB (100), flat from about 0.01 Hz to 3.5 MHz. The circuit Figure 3b is a constant current source supplying 4 mA with the given component values. It could be used as the load in the long-tailed amplifier. Its NPN cousin would be sinking emitter current in that amplifier. With the current mirror, the actual circuit implemented either with discrete components or as a part of a monolithic op amp would look like the circuit in **Figure 4**.

In Part 2 of this article series, I mentioned that few diodes behave exactly as described by the theoretical equations. The opposite is true about transistors. You can use a transistor collector-base or base-emitter junction as an almost ideal diode. What's more, a reverse-biased base-emitter junction

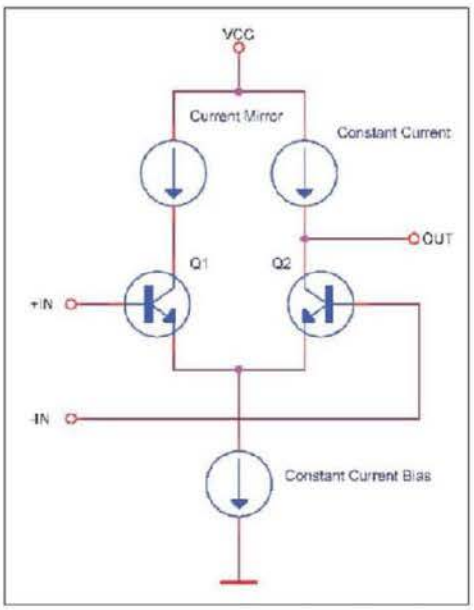

FIGURE 2
Differential pair

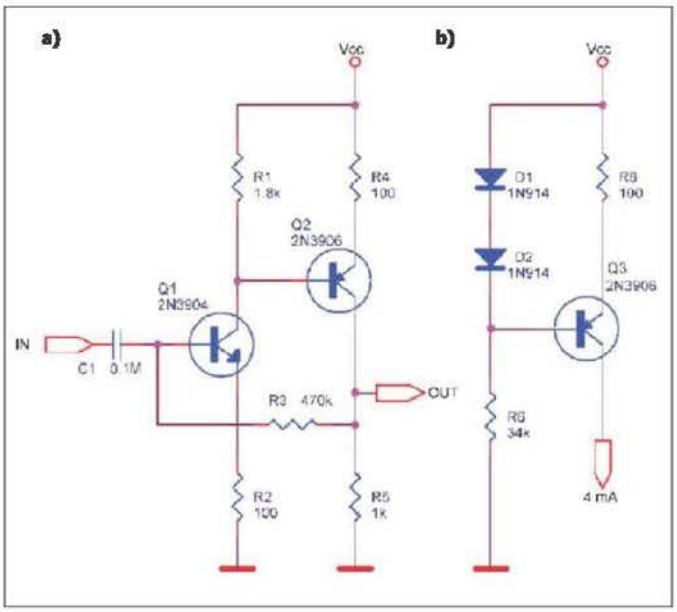

FIGURE 3
A simple complementary amplifier (a) and a constant current source (b)

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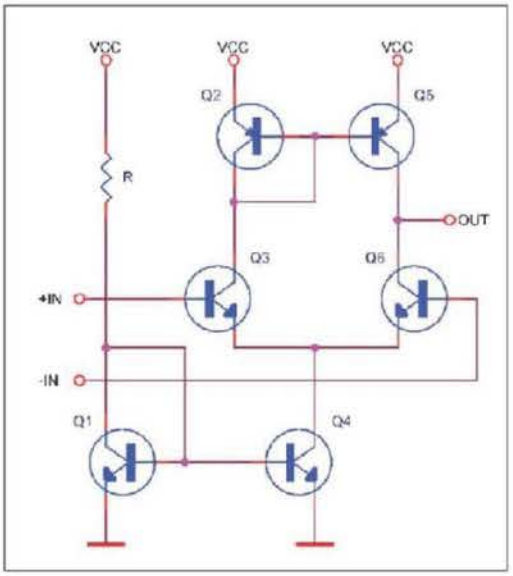

FIGURE 4
Implementation of the long-tailed amplifier using current sources

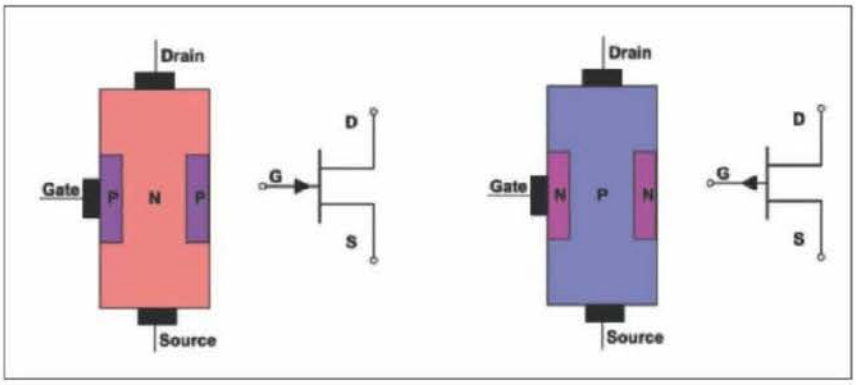

FIGURE 5
Structure of N-channel JFET and schematic symbols of N and P channel. Notice that the Drain and Source electrodes are interchangeable.

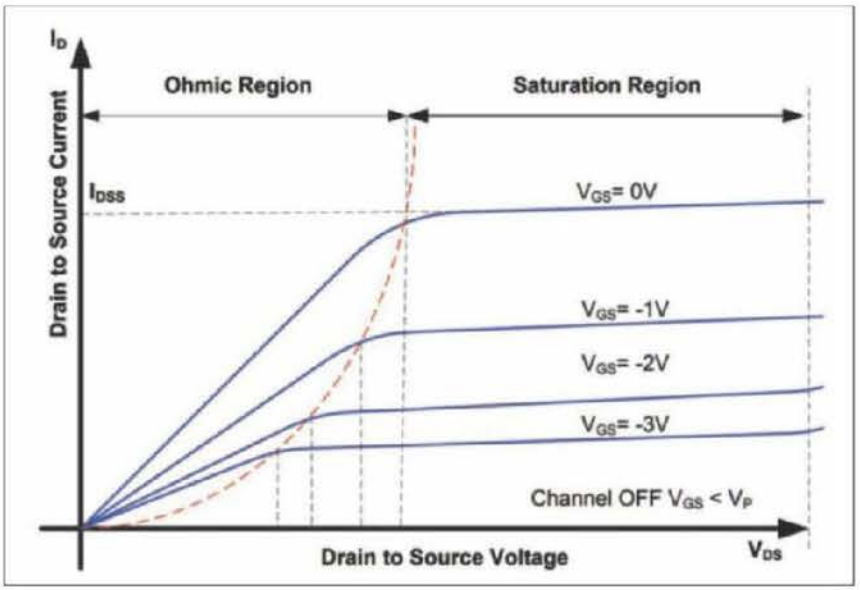

FIGURE 6
JFET Drain I-V characteristics with V_{GS} as parameter

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of a transistor functions as a Zener diode. The popular 2N3904 NPN general purpose transistor, for instance, has a very sharp knee at approximately 6 V, needing just a few microamperes as compared with milliamperes for Zener diodes. This can be useful when power consumption is at premium, as I showed in my past article about infrared detectors (*Circuit Cellar* 343, February 2019).

A LOOK AT FETs

Now, let's turn our attention to field effect transistors—commonly called FETs. Interestingly, the invention of a FET preceded the BJT by some two decades. The FET was patented by Julius Edgar Lilienfeld in 1926, but it was never constructed because the necessary technology wasn't available at that time.

We begin with the JFET structure depicted by **Figure 5** with their accompanying schematic symbols. Just as with the BJTs, JFETs come in two flavors: N-channel and P-channel. You can see that the control electrode called gate is a P-N junction forming a diode. To achieve the FET's signature high input impedance, this diode must be reverse-biased. The result is that the reverse biased gate inhibits the movement of electrons or holes, depending whether the channel is N or P material. The maximum drain-to-source current is obtained at zero bias as shown in **Figure 6**. For this reason, we say that JFETs are depletion-mode devices.

Similar to BJTs, FET amplifiers can also be created in three basic configurations: Common source, analogous to the common emitter: common gate equivalent to the common base and common drain, also known as a source follower corresponding to the emitter follower. Figure 6 is the drain-to-source current I_D versus drain-to-source voltage V_{DS} characteristic with gate-to-source voltage V_{GS} as a parameter. At some negative V_{GS} there will be no I_D current flowing. This negative voltage is referred to as the pinch-off voltage V_P. In the ohmic region the channel resistance can be calculated based on measured drain-source voltage I_{DS} and drain-source current. Then:

$$R_{DS} = \frac{\Delta V_{DS}}{\Delta I_D} = \frac{1}{g_m} \quad [3]$$

where g_m is the FET's transconductance gain.

Common source configuration is widely used, including front end stages of monolithic op amps where it can be often seen as FET-based long-tailed pairs. It has very high input impedance and good voltage gain. Common gate, analogous to the common base, is not as widely used. But it can be seen as the second stage of a cascode amplifier. Once

again, this is analogous to its BJT version with its advantages and disadvantages.

Common drain—in other words, source follower—transforms very high input resistance to a low resistance output. It is frequently an integral part of sensors, such as the passive infrared (PIR). In the saturation region, the saturation current I_{DSS} shows very little dependence on the drain-to-source voltage IDS. This characteristic can be advantageous for the design of constant current sinks and sources.

In a constant current sink (**Figure 7**), resistor R adjusts the magnitude of the sink current which, for R = 0 is the maximum saturation current I_{DSS}. This, as well as the pinch-off voltage, are device dependent. Using a P-channel JFET in place of the N-channel and switching polarities you will obtain a constant current source.

As you may have deduced from Figure 5, the JFET is a symmetrical device and the drain and source terminals are interchangeable. This makes a JFET useful as an analog switch. And if that wasn't enough, JFETs have a fairly wide ohmic region where, based on the V_{GS}, they behave as voltage-controlled resistors. This makes JFETs suitable for applications such as volume control, voltage-controlled oscillators, modulators and wherever a variable resistance is needed. Because of its high input impedance and small geometry, FETs found their use in low noise, high frequency circuits with up to 30 GHz frequency limit.

Next month, in Part 5, will expand our discussion of FETs.

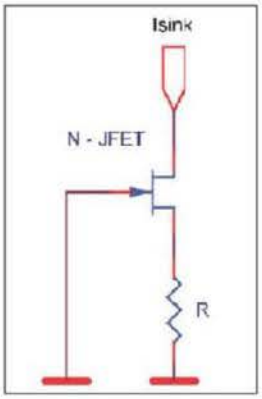

FIGURE 7
Constant current sink built with a N-channel JFET

ABOUT THE AUTHOR

George Novacek was a retired president of an aerospace company. He was a professional engineer with degrees in Automation and Cybernetics. George's dissertation project was a design of a portable ECG (electrocardiograph) with wireless interface. George contributed articles to *Circuit Cellar* since 1999, penning more than 120 articles over the years. George passed away in January 2019, but we're grateful to be able to share with you this, and several more articles he left with us to be published.

COLUMNS

The Consummate Engineer

Semiconductor Fundamentals (Part 5) More on FETs

George continues his article series delving into the fundamentals of semiconductors. In Part 5, he expands his discussion of field effect transistors or FETs. He examines different types of JFETs and MOSFETs, looking at aspects including gate architecture and drain-source I-V characteristics.

COLUMNS

By
George Novacek

Last month we started our discussion of field effect transistors (FETs). Now, let's expand on the topic. The FET was patented by Julius Edgar Lilienfeld in 1926, preceding the invention of the bipolar junction transistor (BJT) by some two decades. But the FET was never constructed, as the necessary technology wasn't available at that time.

Let's start with junction, or JFET structure, as depicted in **Figure 1** with its accompanying schematic symbols. JFETs come in two flavors: N-channel and P-channel. The control electrode called gate is a P-N junction forming a diode which must be reverse-biased to achieve the FET's signature high input impedance. The reverse-biased gate inhibits the movement of electrons or holes, based on whether the channel is of N or P respectively. At zero bias, as shown in **Figure 2**, the maximum drain-to-source current flows. And because the negative gate bias decreases the drain current, the JFETs are called depletion-mode devices.

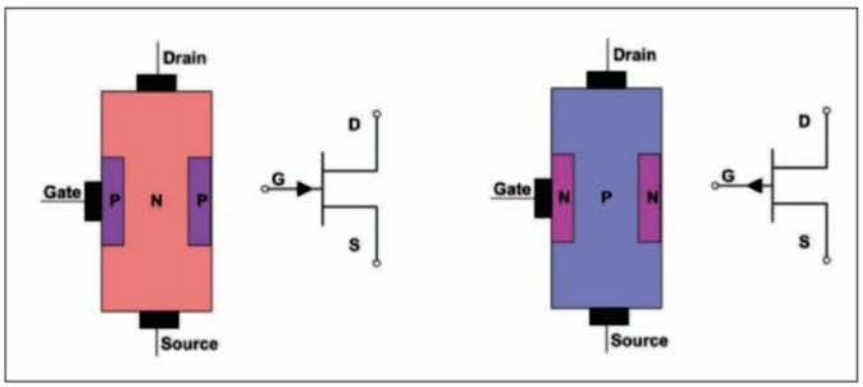

FIGURE 1
Structure of N-channel JFET and schematic symbols of N and P channel

Analogous to BJTs, FET amplifiers can also be created in three basic configurations: Common source, common gate and common drain—the last also known as a source follower. Figure 2 plots the drain-to-source current I_D versus drain-to-source voltage V_{DS} with gate-to-source voltage V_{GS} as a parameter. At some negative V_{GS} called pinch-off voltage V_P the drain current will be zero. In the ohmic region the JFET acts as a voltage-controlled resistor:

$$R_{DS} = \frac{\Delta V_{DS}}{\Delta I_D} = \frac{1}{g_m} \quad (1)$$

where R_{DS} is the channel resistance and g_m is the FET's transconductance gain.

JFETs' dice are smaller than BJTs'. So, the common source JFETs are often used in the long-tailed pair configuration in front-end stages of monolithic op amps. This topology has very high input impedance and good voltage gain. Common gate topology can be seen as the second stage of a cascode amplifier, also

analogous to the BJT version with the same advantages and disadvantages. The source follower is frequently an integral part of high resistance sensors—such as the pyroelectric ones—because it matches their high input resistance to a low resistance output.

In saturation the I_{DSS} current shows very little dependence on the drain-to-source voltage. This makes the design of constant current sinks and sources easy (**Figure 3**). Resistor R adjusts the magnitude of the sink current which, for R = 0 is the maximum saturation current I_{DSS}. To set a lower current the resistor R value is increased. A P-channel JFET operated at opposite polarities forms a constant current source.

JFET APPLICATIONS

As shown in Figure 1, JFET is a symmetrical device, so the drain and source terminals are interchangeable. This property makes JFET useful as an analog switch or a voltage-controlled resistor. Applications include volume control, voltage-controlled oscillators, modulators and wherever a variable resistance is needed. Because of their high input impedance and small geometry, FETs also find their use in low noise, high frequency circuits up to about 30GHz.

Figure 4 is a basic N-channel, common source JFET amplifier. When setting up its DC operating point you must remember to keep the gate electrode negatively biased with respect to source. Here the gate is connected to the ground potential $V_G = 0$ and the source electrode's potential is raised by drain current I_D through resistor R_S to V_S, just as we used to bias triodes. With the working I_D established from the JFET I-V diagram, you compute resistor values R_S and R_D to set V_D to approximately $(V_{DD} - V_S)/2$. Of course, you need to know the JFET characteristics—unfortunately, specification sheets I have checked give you very little data—just enough for designing an analog switch, but nothing more. You need to do some measurements of your own.

In the Figure 4 amplifier example I used J110 JFET with R_G= 1MΩ, R_S = 470Ω and R_D = 1kΩ. The DC operating point of this amplifier was V_S = 2.3V, V_D = 7.15V, V_G = 0V and V_{DD} = 12V. To obtain a useful AC gain I bypassed R_S with a 100µF capacitor, which resulted in the gain of 23dB (AV ≈14), - 3dB flat from 26Hz to 21MHz.

As mentioned earlier, JFETs come as N-channel and P-channel. The N-channel is doped with donor impurities and, therefore, the current through the channel is negative in the form of electrons. The P-channel is doped with acceptor impurities and, consequently, the current through the channel is positive in the form of holes. Because electrons have higher mobility than holes, N-channel JFETs exhibit greater channel conductivity (lower resistance) than their P-channel counterparts. The N-channel JFET is more efficient and, therefore, while available, P-channel JFETs are not as frequently used.

MOSFETs

The next step is to contemplate the metal-oxide semiconductor field effect transistor or MOSFET. Just like bipolar transistors and JFETs, MOSFETs come as N and P types. Additionally, each type can be an enhancement or depletion, so that makes our MOSFET types. Most digital ICs today—including microprocessors, microcontrollers,

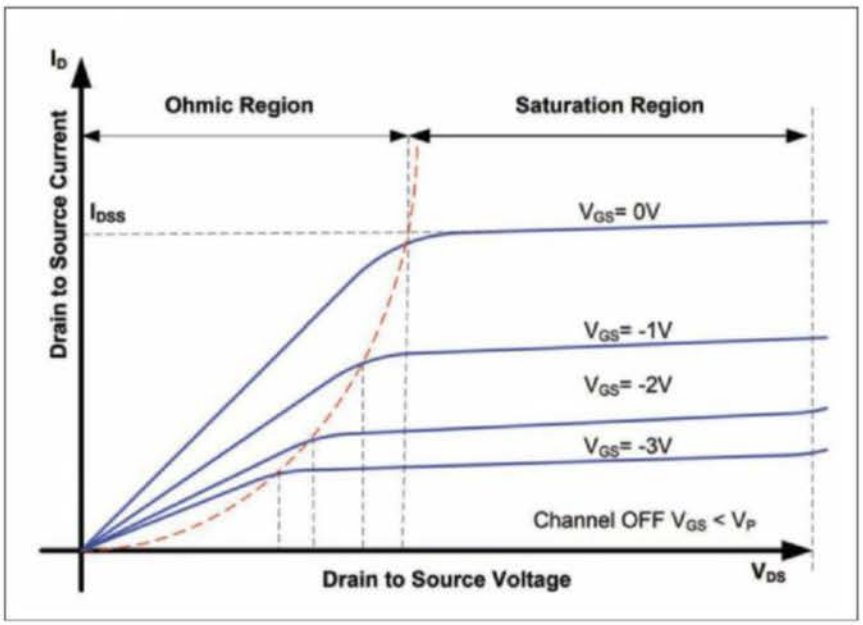

FIGURE 2
JFET Drain I-V characteristics with V_{GS} a parameter

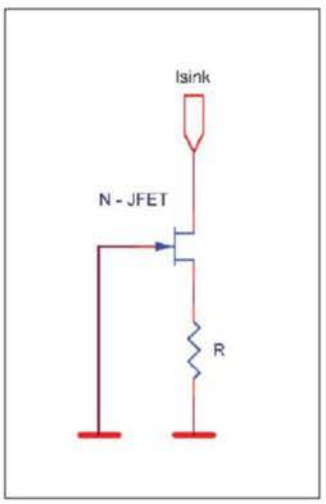

FIGURE 3
N-channel JFET constant current sink

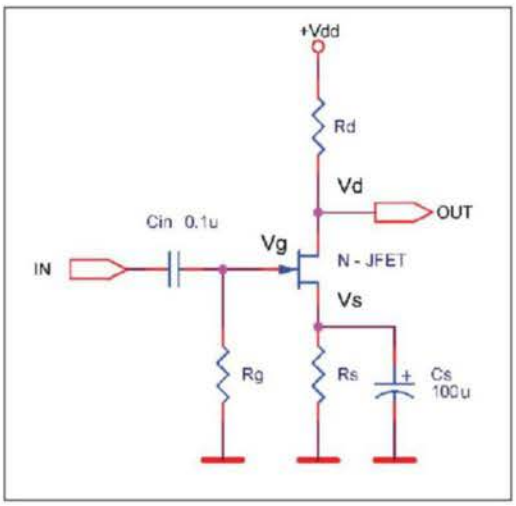

FIGURE 4
A common source low frequency amplifier

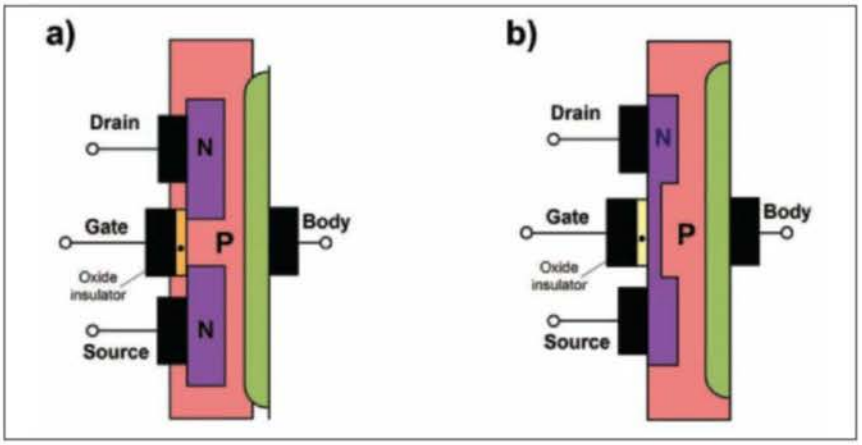

FIGURE 5
Cross-section of N-channel enhancement (a) and depletion (b) type MOSFET

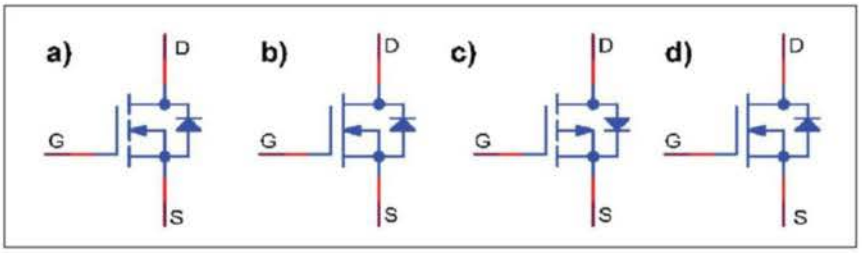

FIGURE 6
Shown here are the symbols of enhancement (a) and depletion (b) type N-channel MOSFETs and enhancement (c) and depletion (d) type P-channel MOSFETs. No bulk terminals are present.

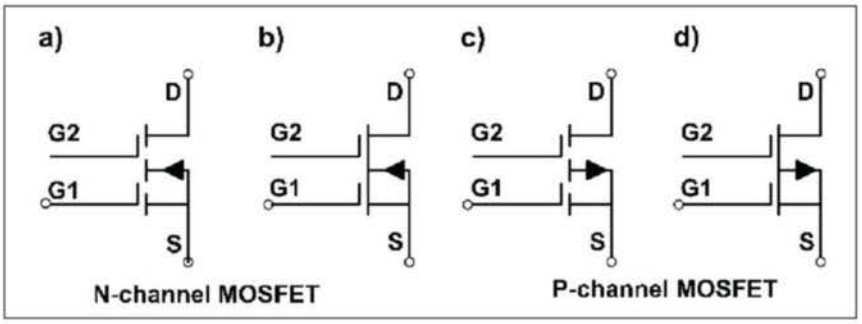

FIGURE 7
Here are the symbols of dual gate enhancement (a) and depletion (b) type N-channel MOSFETs and dual gate enhancement (c) and depletion (d) type P-channel MOSFETs.

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storage devices and so on—are made using MOSFET technology. In the '70s, purely PMOS or NMOS ICs had been fabricated, but today complementary pairs of the N- and P-channel transistors let us build CMOS devices with high speed and low power consumption.

The main difference between the JFET and the MOSFET is that the MOSFET gate is isolated from the body of the semiconductor by an oxide insulator. Therefore, an extremely high input resistance to the tune of 1,012Ω is obtained. I used such a MOSFET to interface with an ionization chamber that had a cross-current around 1-2nA. Because the gate could be easily destroyed by static electricity discharge, many MOSFETs have an internal diode protection, somewhat degrading the high input resistance.

Figure 5a illustrates the N-channel enhancement MOSFET structure, **Figure 5b** shows the N-channel depletion mode structure. Notice that MOSFETs have a fourth electrode called body, bulk or substrate. It is generally connected to the source potential. Many MOSFETs have the connection done internally and no lead outside the enclosure. Also notice that the substrate-to-drain and substrate-to-source junctions form intrinsic diodes. With the bulk usually connected to the substrate, the substrate-to-source diode is shorted. But the substrate-to-drain diode is the reason why the MOSFET drain and source are not interchangeable. The diodes are shown in the MOSFET symbols (**Figure 6**). The P-channel MOSFET's structure looks the same, just the polarities are reversed. The N-channel enhancement MOSFET, in my experience, is the most prevalent for switching and digital applications.

By now MOSFETs have replaced BJTs in many applications, including communications reaching up to the many gigahertz. Dual gate MOSFETs were developed especially for applications as oscillators, mixers, multipliers, amplifiers and so forth in RF, VHF, UHF, microwave and higher frequency ranges. Both gates affect the operation of the device, which could be viewed as two MOSFETs in series. Their respective symbols are shown in **Figure 7**. Notice the intrinsic diode is not always shown in the MOSFET symbol.

A dual gate MOSFET can form a cascode amplifier overcoming the Miller effect as discussed previously. The Miller effect relates to the impedance between the output and the input, but at high frequencies capacitance is the predominant factor, potentially leading to instability. Biasing Gate 2 (also called the drain gate) at a constant potential, well bypassed to the ground, eliminates the capacitive coupling and thus the Miller effect.

The I-V characteristic of depletion MOSFETs

ABOUT THE AUTHOR

George Novacek was a retired president of an aerospace company. He was a professional engineer with degrees in Automation and Cybernetics. George's dissertation project was a design of a portable ECG (electrocardiograph) with wireless interface. George contributed articles to *Circuit Cellar* since 1999, penning more than 120 articles over the years. George passed away in January 2019, but we're grateful to be able to share with you this, and a couple more articles he left with us to be published.

is similar to that of the JFETs in Figure 2. Enhancement MOSFETs need some minimum gate to source voltage to begin to conduct as seen in **Figure 8**. Design of an amplifier with enhanced mode MOSFETs is along the same lines as described earlier for JFETs. Just the gate biasing is different. MOSFETs intended for logic switching applications guarantee minimum R_{DS}—in other words, the drain-to-source resistance, often in milliohms, at the gate voltages less than 5V.

BUILDING BLOCKS

Some readers may think discussing discrete components unnecessary. Thanks to the availability of many inexpensive integrated circuits (ICs) and system building blocks, circuit design with discrete components is becoming almost an arcane art. But, all that said, transistors are the building blocks of ICs—devices that many make a living designing. And even if IC design is not in your future, understanding their underlying principles can only help with product designs and troubleshooting.

We'll complete the series next month with a look at power MOSFETs and some nearly exotic components with multiple P-N junctions.

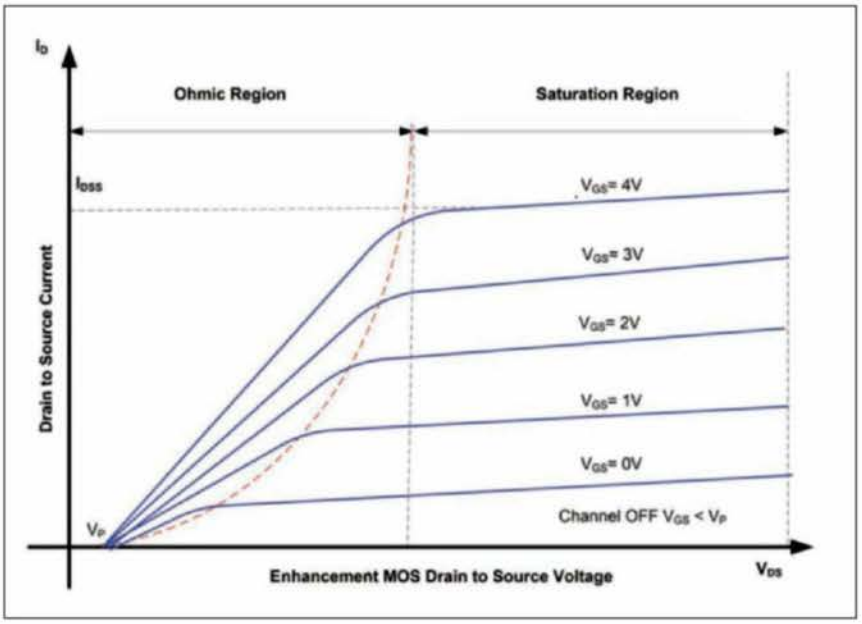

FIGURE 8
Drain-source I-V characteristics of an enhancement type N-channel MOSFET

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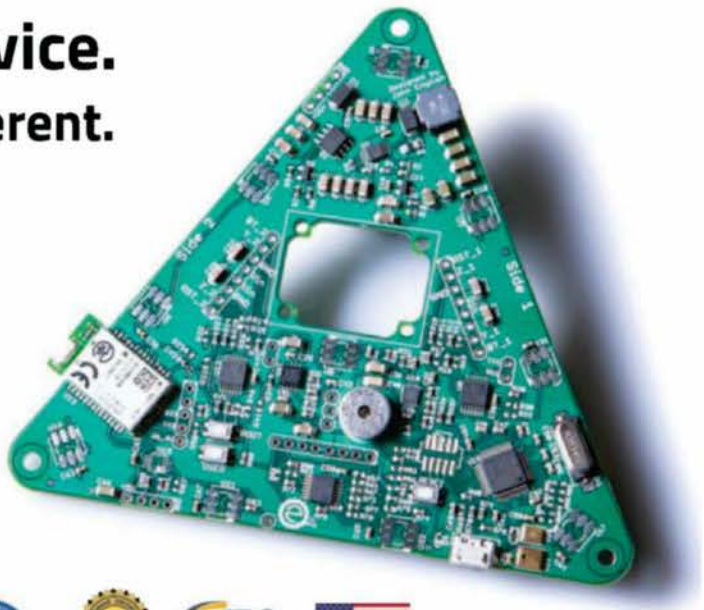

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The Consummate Engineer

Semiconductor Fundamentals (Part 6) High-Power MOSFETs

George continues his article series looking at all aspects of the basic structures that make semiconductors work. In Part 6—his final article of the series—he builds on last month's exploration of MOSFETs by this time examining MOSFETs designed specifically to handle high power.

By
George Novacek

Last month's article was dedicated to metal oxide semiconductor field-effect transistor or MOSFET designed to handle signals and power of relatively low level. Now let's look at MOSFETs designed specifically to handle high power. Among the advantages of power MOSFETs are their high switching speed and good efficiency. At operating voltages less than 200V, the power MOSFET is the king. It is found in various applications from switching power supplies and motor controllers to analog amplifiers.

Power MOSFETs come in three major categories: N-channel enhancement, P-channel enhancement and N-channel depletion—with the N-channel enhancement being the most popular and achieving the lowest $R_{DSon.}$ P-channel depletion type power MOSFETs theoretically exist but I haven't found one commercially available. MOSFETs offer high input impedance and a forward voltage drop decreasing with temperature. That ensures even current distribution. As a result, power MOSFETs can be paralleled to achieve the desired current handling capability. Keep in mind that—like all other MOSFETs—power MOSFETs also contain the intrinsic bulk diode.

Vertical Diffused MOS (VDMOS)—also known as Double-Diffused MOS (DMOS)—is the most prevalent power MOSFET structure today. Its cross-section is depicted in **Figure 1**. With the source electrode on the top and the drain electrode at the bottom of the device, the current flow through the device is vertical. The P wells and N+ regions are manufactured by a process called double diffusion—hence the "double-diffused" in its name.

Unlike most signal devices that are planar, the structure of most power devices is vertical. That's because the current handling capability depends on the channel width and the vertical structure allows the die area to be minimized, which also keeps the cost low. Furthermore, the transistor has a cellular structure where essentially a number of transistor cells work in parallel. The most common cell shape is hexagonal, introduced by International Rectifier (now Infineon Technologies), With that in mind, they gave the name Hexfet to their line of power MOSFETs. For use in some analog applications, such as high-end audio amplifiers or microwave/RF, power MOSFETs with lateral structure (LDMOS) are manufactured.

SELECTING POWER MOSFETs

To select a power MOSFET, you need to decide on several characteristics. For starters—especially for switching applications—R_{DSon}, the drain-to-source resistance when the device is fully turned on—is very important. It determines the voltage loss across the MOSFET and, therefore, its power dissipation. Devices with R_{DSon} in the range of milliohms are commonly available.

You also need to make sure the maximum gate-to-source and drain-to-source voltages are not exceeded. Typically, the maximum gate-to-source voltage V_{GS}

is about 20V, but many power MOSFETS are fully on at a V_{GS} of 5V or less. Increasing the drive voltage beyond that level makes no sense. It does not decrease the R_{DSon}, but it does age the MOSFET reducing its life. For the maximum drain-to-source voltage $V_{DS,}$ I always try to select a device with at least double the operating voltage. **Figure 2** shows the typical power MOSFET I-V characteristic. It is not dissimilar to the enhancement type signal MOSFET as discussed in Part 5 of this article series (*Circuit Cellar* 354, January 2019).

Obviously, not exceeding the maximum drain-to-source current I_{DS} is just as important for the reliable operation of the transistor. Specification sheets contain graphs defining the safe operating area within which the MOSFET can perform without being damaged.

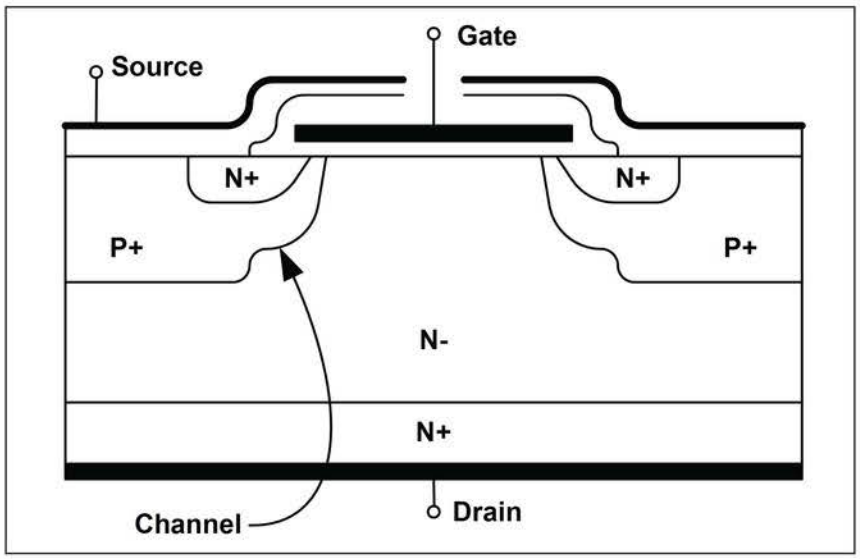

FIGURE 1
Cross-section of VDMOS

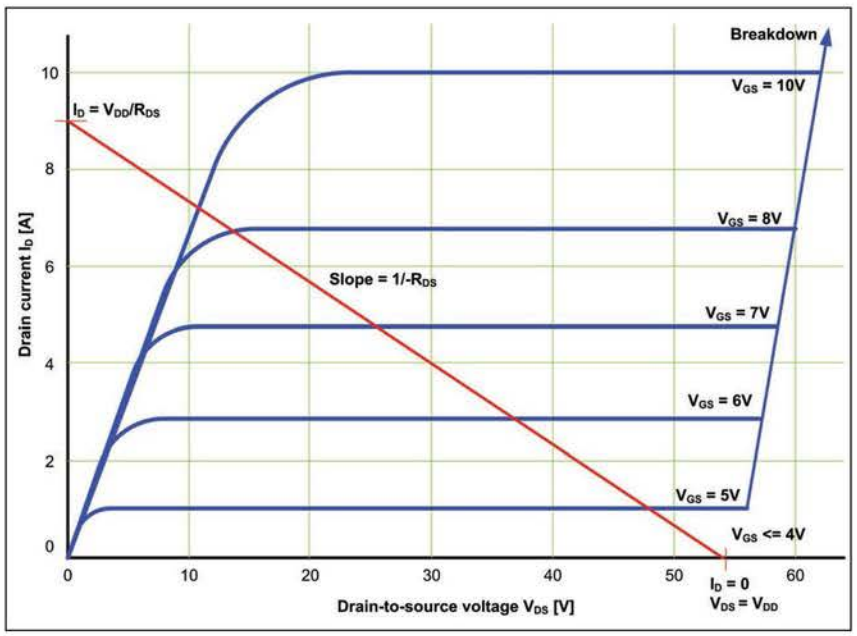

FIGURE 2
Typical I-V characteristic of a power MOSFET with the load line shown in red

Dynamic behavior—in other words, switching behavior—of the MOSFETs is guided not only by their R_{DSon} but also by their intrinsic capacitances and reverse recovery characteristics. The input capacitance C_{ISS} is the sum of the gate-to-source capacitance C_{GS} + gate-to drain capacitance C_{GD}. The output capacitance C_{OSS} is the sum of the drain-to-source capacitance C_{DS} + the gate-to-drain capacitance C_{GD}. And, finally, the reverse transfer capacitance C_{RSS} equals to the gate-to-drain capacitance C_{GD}.

To turn the MOSFET on and off, the driver must be able to overcome the gate charge, which can be expressed as an integral as follows:

$$Q_G = \int i_{GG}(t)\,dt \qquad [1]$$

To turn the saturated device off, the driver needs to absorb in a given time—also known as the storage time—the excess reverse recovery charge. Numerous gate drivers are commercially available to suit just about any MOSFET driving requirement. **Figure 3** shows a simple power MOSFET switch.

While there are many possible configurations, Figure 3a shows major concerns the circuit designer has to address. To begin with, resistors R1 and R2 are there to protect the sensitive gate. As a voltage divider, R1 and R2 ensure the gate voltage VGS is adequate to turn the MOSFET fully on, while at the same time it makes sure the V_{GS} does not exceed the safe limit. R2 also ensures that, should the driving circuit become open, the gate will not float or become subject to static charges. The Zener diode D1 is not always needed, but if an analysis reveals a failure mode that could result in V_{GS} exceeding the allowed maximum, D1 will safely clamp it below that level.

The requirement for including the freewheeling diode D2 in the circuit depends on the characteristic of the load. Inductive loads—such as relays or motors—do require it to dissipate the back electromagnetic force (EMF) generated when the load is disconnected. The back EMF, depending on the load characteristics and how fast the MOSFET disconnects, can reach hundreds of volts, exceeding the device's breakdown voltage. But don't be fooled by "purely resistive" loads. Just their wiring can introduce a considerable inductance into the circuit.

Complementary combinations of N-channel and P-channel MOSFETs, as shown in Figure 3b, are popular in half-bridge and full-bridge configurations to drive loads such as motors, when polarity reversal is a

requirement. Here, once again freewheeling diodes need to be employed, but are not shown for simplicity. The bridge driver has an additional feature: It can short-circuit the motor armature and cause a reverse current to flow through the windings. That acts as an efficient electrical brake. In some applications, such as trains for example, the EMF is used to recharge storage batteries.

Another issue I want to bring to your attention is that, in a half or a full bridge configuration, you must make sure that in the complementary pairs, the two transistors are never turned on at the same time, essentially acting as a crowbar across the power supply. While Figure 3b is representative of CMOS logic and can be used in some low power applications, in high power circuits all four MOSFET gates have individual inputs to ensure they are switched at a correct sequence. For that you can design or purchase an appropriate driver circuit or use four separate output pins of a microcontroller.

CONTROL VIA PWM

MOSFET switches provide efficient power control through pulse-width modulation (PWM). Lights, heaters, motors and other devices are common candidates for this type of control. Unfortunately, not all electrical loads respond well to PWM. This is rarely mentioned in specification sheets, so it's up to you to test it. Once I needed to control the speed of a couple of 12VDC fans. The PWM controlled the speed all right, but the fans emitted a rather unsettling squeal.

Lowering the repetition rate caused jerky (and audible) rotation of the fans, while increasing it beyond hearing range resulted in the fan motors to cease to respond. Not willing to buy and test another set of fairly expensive fans, I ended up integrating the pulses by a capacitor with a source follower into a DC voltage. It worked, but a large heatsink on the power transistor was the price to pay.

Because the silicon-based power MOSFETs have reached their theoretical limits, gallium-nitride (GaN) based FETs were introduced in 2010. GaN is a high electron mobility semiconductor (HEMT), providing the new transistors with many advantages.

GaN has an electric field strength higher than silicon, and in combination with its higher electron mobility GaN devices are able to be smaller with smaller R_{DSon} and a higher breakdown voltage than a comparable silicon MOSFET. GaN FETs come as enhancement and depletion mode devices, which can replace the silicon MOSFETs in many circuits.

GaN devices—due to their lateral structure—feature a very low intrinsic capacitance, and are able to switch hundreds of volts within a matter of nanoseconds. There is no parasitic PN junction found in silicon devices, which is the reason for the intrinsic bulk diode. However, different mechanism creates a similar diode inherent in the GaN FETs. The low GaN FET capacitances responsible for its extremely high switching speed require precise PCB layout to avoid instabilities.

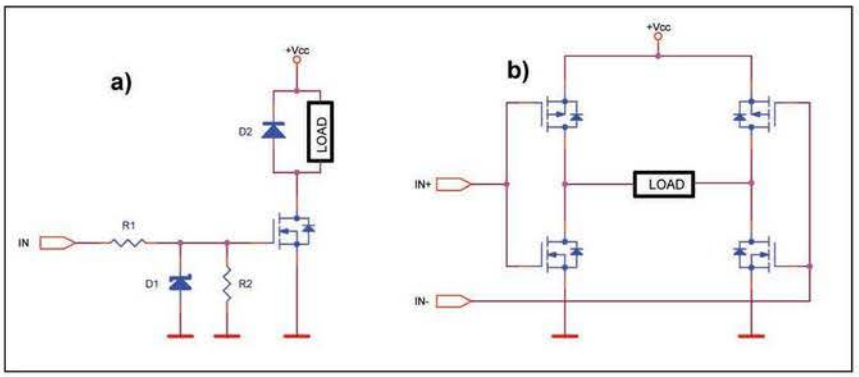

FIGURE 3
Basic configurations of power MOSFET switches including a simple MOSFET switch (a) and complementary combinations of N-channel and P-channel MOSFETs (b)

There are other semiconductor devices—such as IGBTs, thyristors, PUTs and others—that I didn't cover in this article series. But I touched on those in my article "Electrical Power Converters (Part 3) in *Circuit Cellar* 320 (March 2017). Thanks to the present-day availability of many inexpensive ICs and system building blocks, circuit design with discrete components is becoming almost an arcane art. But then again, transistors are building blocks of ICs and many engineers make a living designing those. Even if IC design is not in your future, having an insight into the underlying principles of the solid-state technology can only help you with future projects.

COLUMNS

ABOUT THE AUTHOR

George Novacek was a retired president of an aerospace company. He was a professional engineer with degrees in Automation and Cybernetics. George's dissertation project was a design of a portable ECG (electrocardiograph) with wireless interface. George contributed articles to *Circuit Cellar* since 1999, penning more than 120 articles over the years. George passed away in January 2019, but we're grateful to be able to share with you this, and a couple more articles he left with us to be published.

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